Biogeochemical typology and temporal variability of lagoon waters in a coral reef ecosystem subject to terrigeneous and anthropogenic inputs (New Caledonia)

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Keywords:
Coral reef lagoon
Nutrients
Hydrology
Typology
Temporal variability
Trophic status

Abstract

Considering the growing concern about the impact of anthropogenic inputs on coral reefs and coral reef lagoons, surprisingly little attention has been given to the relationship between those inputs and the trophic status of lagoon waters. The present paper describes the distribution of biogeochemical parameters in the coral reef lagoon of New Caledonia where environmental conditions allegedly range from pristine oligotrophic to anthropogenically influenced. The study objectives were to: (i) identify terrigeneous and anthropogenic inputs and propose a typology of lagoon waters, (ii) determine temporal variability of water biogeochemical parameters at time-scales ranging from hours to seasons. Combined ACP-cluster analyses revealed that over the 2000 km² lagoon area around the city of Nouméa, “natural” terrigeneous versus oceanic influences affecting all stations only accounted for less than 20% of the spatial variability whereas 60% of that spatial variability could be attributed to significant eutrophication of a limited number of inshore stations. ACP analysis allowed to unambiguously discriminating between the natural trophic enrichment along the offshore–inshore gradient and anthropogenically induced eutrophication. High temporal variability in dissolved inorganic nutrients concentrations strongly hindered their use as indicators of environmental status. Due to longer turn over time, particulate organic material and more specifically chlorophyll a appeared as more reliable nonconservative tracer of trophic status. Results further provided evidence that ENSO occurrences might temporarily lower the trophic status of the New Caledonia lagoon. It is concluded that, due to such high frequency temporal variability, the use of biogeochemical parameters in environmental surveys require adapted sampling strategies, data management and environmental alert methods.

1. Introduction

The impact of anthropogenically enhanced runoff and chemical inputs to the coastal zone is acknowledged as a worldwide scale issue (see reviews in Sheppard (2000)). Coral reef environments are strongly affected by global change and due to prevailing oligotrophic conditions they are commonly considered as sensitive environments easily altered by even moderate anthropogenic inputs (Adey et al., 2000). As a consequence, community structure alterations observed during the past two decades have often been empirically related to anthropogenic alteration of environmental conditions. Considering this repeated claim, the paucity of existing recent papers dealing with the spatial and temporal variability of hydrology in coral reef lagoons is anachronistic. Moreover, most of the available recent studies on lagoon water chemical status deal with atoll reef environments subject to insignificant anthropogenic inputs (Charpy-Roubaud et al., 1990; Delesalle and Sournia, 1992; Charpy et al., 1997; Le Borgne et al., 1997; Pages et al., 2001; Dufour et al., 2001) whereas environmental assessment study of barrier reef lagoons exposed to significant terrigeneous and anthropogenic inputs prove to be surprisingly scarce (Erftemeijer and Herman, 1994; Morrison and Naqasima, 1999; Muslim and Jones, 2003). Despite the high number of publications dealing with coastal environment alterations, few really focused on the distribution and temporal variability of biogeochemical parameters in the water (Larned, 1998; Liston et al., 1992; Muslim and Jones, 2003) and a lot of datasets have been published and discussed in books or grey literature reports (Haynes et al., 2001; Furnas, 2003). The Great Barrier Reef region received some significant attention on environmental status assessment and temporal
variability (Devlin and Brodie, 2005; Fabricius et al., 2005; Moss et al., 2005; Udy et al., 2005; Woodridge et al., 2006; Brodie et al., 2007) and similar efforts yielding information on environmental typology has to be applied to other reef areas worldwide. Such an evolution is urgently needed as relationship between coral reef health and terrigeneous or anthropogenic inputs have often been stated when proper information on environmental status was so evidently missing.

As part of a several year programme studying environmental issues in Pacific high island coral reef lagoons, an intensive study on water biogeochemistry was conducted to precisely define environmental status in the southern part of the New Caledonia west coast lagoon close to the city of Nouméa. The objectives defined were:

- To define the distribution of biogeochemical parameters in a lagoon subject to combined oceanic, terrigeneous and anthropogenic influences.
- To propose a simplified typology of lagoon waters.
- To assess the magnitude of temporal variability of water biogeochemical parameters at time-scales ranging from hours to seasons considering that this aspect has rarely been investigated despite the major constraints it exerts on the implementation of environmental surveys (see also Le Borgne et al. (2010); Torreton et al. (2010)).

2. Material and methods

2.1. Study site

New Caledonia is a French overseas country (Jost, 1998) located in the Pacific Ocean between latitudes 19° and 23° south and longitudes 163° and 168° east, just to the north of the Tropic of Capricorn, (Fig. 1). The coral barrier reef of New Caledonia delimits a large lagoon. Water temperature in the lagoon tends to be 1–2 °C lower in winter and 1–2 °C higher in summer than in the ocean (Rougerie, 1986; Le Borgne et al., 2010). Salinity is generally close to ocean salinity but in protected bays it may decrease due to occasional rainfalls or increase during period of droughts which are especially pronounced during ENSO events (Ouillon et al., 2005, 2010). On the southern part of the west coast where the study was conducted, rainfalls are moderate and it is extremely rare for estuarine plumes to extend as far as the reef which is more than 10 km away from the coast (Labrosse et al., 2000). The semi-diurnal tide, with amplitudes of 1.5 m at spring tide and 0.3 m at neap tide, propagates from the south to the north and its influence on lagoon circulation is largely depending on the geomorphology (Douillet, 1998). Trade winds favour rapid renewal rate of lagoon water and recent hydrodynamic modelling work calculated an average residence time of no more than 11 days for the south-west part of the lagoon that covers an area of 2000 km² (Bujan et al., 2000; Jouon et al., 2006; Ouillon et al., 2010). Lagoon water quality hence is considered as chiefly determined by ocean water inflow, land originating inputs and anthropogenic inputs mainly originating from industrial and waste water discharges and mining activities (Labrosse et al., 2000).

2.2. Sampling

The sampling was conducted on a total of 23 cruises covering the 1997–2001 period (Table 1) and over 33 stations located along land-reef transects were sampled from March 1997 to November 1999. This data set was mainly used to establish seasonal variability for a limited number of stations typical of the main lagoon subsystems. In complement, surveys were conducted over periods of time of 1–7 days to assess high frequency variability. Finally, a stronger sampling effort was invested in September 2000 (87 sampling stations) and March 2001 (86 sampling stations) during cruises dedicated to assessing the distribution of chemical parameters at the scale of the whole lagoon.

Fig. 1. Study site – location and bathymetric map of the study site in the lagoon of New Caledonia, distribution of cruises sampling stations.
### 2.5. Data analysis

Data interpretation called for a reliable multi-parametric approach of the complex hydrochemical data set generated by the two cruises of September 2000 and March 2001. Our goal was to identify the main sources of influence, assess the existing correlations between environmental variables and establish a statistically supported water typology. Data analysis was conducted using a combination of principal component analysis (PCA) and cluster analysis (Legendre and Legendre, 1998). The PCA was conducted on the correlation matrices (i.e. standardized variables) of 12 variables (Sal, turb, Cha, Pheo, NH₄⁺, NO₃⁻, PO₄³⁻, Si(OH)₄, DN, DP, POP, and PON) versus 87 (September 2000) or 82 (March 2001) sampling stations. Additional classification was obtained by conducting an agglomerative cluster analysis on the correlation matrices resulting from the PCA (Webster and Oliver, 1991; Lebart et al., 1995). Combined PCA and cluster analysis classification results were plotted on biplots representing the two first principal component axes PC1 and PC2 as they jointly accounted for more than 70% of spatial variability. Indexes of average water residence time such as “water age” or “local e-flushing time” were calculated for each sampling station and used in the PCA analysis as explanatory variables.

### 2.3. CTD profiles

Salinity profiles were obtained from a SeaBird SBE 19 CTD equipped with additional turbidity (Seapoint optical back scatter) and in situ fluorescence (Wet Lab Wetstar) sensors. Salinity was obtained with a precision of 0.001 while calibrated back scattering turbidity sensors provided NTU data with a precision of 0.1 NTU. In coral reef lagoons, where various origins of particles provide a multi-modal particle size distribution, it has been demonstrated that back scattering is linearly correlated to suspended particulate matter concentrations of less than 10 g L⁻¹ with a correspondence of 1 NTU for 1 mg with negligible variability between individual nephelometers (Larcombe et al., 1995; Bunt et al., 1999; Ouillon et al., 2004). In situ fluorescence is presented as arbitrary fluorescence units with a precision of 0.01 units. The correspondence from in situ fluorescence to chlorophyll a ($R^2 > 0.7$) or pheopigment ($R^2 > 0.5$) concentrations was calculated using coincidental discrete sub-surface sampling, sampled water filtration on Whatman GF/F filters and in vitro fluorescence measurements.

### 2.4. Particulate and dissolved material

Discrete water samples were taken using a Niskin bottle at 3 m depth. Samples for the fluorometric determination of ammonia (Kérouel and Aminot, 1997; Holmes et al., 1999) were determined at nanomolar concentrations (Raimbault et al., 2004). In situ fluorescence is presented as arbitrary fluorescence units with a precision of 0.01 units. The correspondence from in situ fluorescence to chlorophyll a ($R^2 > 0.7$) or pheopigment ($R^2 > 0.5$) concentrations was calculated using coincidental discrete sub-surface sampling, sampled water filtration on Whatman GF/F filters and in vitro fluorescence measurements.

### Table 1

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#### 3. Results and discussion

#### 3.1. Distribution of environmental variables

The distribution of sub-surface (2–4 m depth averaged) turbidity in September 2002 (Fig. 2a) showed highest suspended loads in the Bay of Sainte-Marie, and the Bay of Dumbéa, maximum values of more than 3.5 NTU being reached in the inner parts of Koutio Bay and Grande Rade. Turbidity levels of more than 2.5 NTU were recorded in Boulari Bay close to the estuary of La Coulée River but no significant turbidity increase was observed at the mouth of Les Pirogues River. Turbidity of less than 0.5 were recorded in most part of the middle lagoon except at station M38 in the back reef area were an average turbidity of 1.2 NTU was recorded. This value however only corresponded to a 3 m surface layer lying over a 20 m deep layer of water with a turbidity of 0.5 NTU. Turbidity levels in March 2001 (Fig. 2c) were comparable to those measured in September 2000 except for a peak over 4 NTU in the north-west back reef area and at the mouth of Les Pirogues River. In this latter case it is important to note that, due to the low sampling resolution in this area, data interpolation tends to overestimate the spreading of the actual plume.

In September 2000 and March 2001, chlorophyll a concentrations (Fig. 2b and f) of more than 0.8 µg L⁻¹ were measured in Sainte-Marie Bay as well as in Grande Rade and Koutio Bay, the two urbanised embayments in Dumbéa Bay. Lower chlorophyll concentrations were measured at the mouth of rivers (Port Laguerre, La Coulée, Les Pirogues) suggesting moderate nutrient inputs from the river. Higher concentrations (0.4–0.8 µg L⁻¹) recorded close to the Dumbéa estuary was very likely to originate from the extension of Koutio Bay inputs. Chlorophyll a concentrations were slightly higher in March 2001 than in September 2000 in the middle lagoon with concentrations between 0.2 and 0.5 µg L⁻¹. The chlorophyll a versus pheopigment ratio was remarkably constant at 1.1 with a standard deviation of 0.12 in September and at 1.34 with a standard deviation of 0.36 in March with no significant modification in this average ratio even under chloropigment enrichment conditions.

Whatever the period, PON (Fig. 2c and g) and POP (Fig. 2d and h) distributions were very similar to the distribution of chlorophyll a. In September 2000 concentrations in PON ranged between 0.5 and 0.9 µM in the lagoon and increased to more than 1.9 µM in the inner part of the three urbanised bays located around the city of Nouméa. Similarly, POP concentrations ranged between 0.02 and 0.06 µM in the lagoon and increased to more than 0.16 µM in the...
Fig. 2. Spatial distribution of particulate material – distribution of turbidity, chlorophyll $a$, particulate organic nitrogen (PON) and phosphorus (POP) in the New Caledonia lagoon around the city of Nouméa during two cruises conducted in September 2000 and March 2001.
Fig. 3. Spatial distribution of dissolved material – distribution of ammonia (NH₄⁺), nitrate + nitrite (NO₃), dissolved total nitrogen (DN) and silicate (Si(OH)₄) in the New Caledonia lagoon around the city of Nouméa during two cruises conducted in September 2000 and March 2001.
inner parts of the three bays. In March 2001, PON and POP concentrations in the middle lagoon were globally higher than in September 2000 commonly reaching values between 0.7 and 1.5 μM and 0.04 and 0.08 μM for PON and POP, respectively. Similarly, concentrations in the coastal urbanised bays were higher in March 2001 than in September 2000. A slight increase in POP and PON concentrations was measured in the north-west part of the lagoon when compared with the south-east part, a situation that could be due to a conjunction of higher water residence time and inputs of combined terrigeneous and anthropogenic inputs.

During the September 2000 cruise, ammonia concentrations (Fig. 3A) of more than 0.7 μM were measured at the four inner sampling points in Sainte-Marie Bay and in the very inner part of Koutio Bay. NH$_4^+$ concentrations rapidly decreased to less than 0.2 μM in the south-east part of the lagoon and to less than 0.3 μM in its north-west part. The situation in March 2001 (Fig. 3E) was entirely different as NH$_4^+$ concentrations were below 0.2 μM through the whole lagoon except for a small increase to 0.3 μM in the inner part of Boulari Bay.

In September 2000, highest nitrate concentrations (Fig. 3B) were measured in Sainte-Marie Bay and in the inner part of Dumbea Bay including Koutio Bay and the waters around the mouth of Dumbea River. High concentrations were measured at two sampling sites in the north-west back reef area, hence far away from any source of terrigeneous or anthropogenic inputs. NO$_3^-$ concentrations were below 0.03 μM in most other parts of the lagoon. In March, NO$_3^-$ concentrations (Fig. 3F) of more than 0.1 μM were measured in Koutio Bay. Outside this bay, NO$_3^-$ concentrations were mostly below 0.04 μM except for the middle part of the lagoon where concentrations of more than 0.08 μM were recorded at three stations with a peak at 0.12 μM at station M33.

The distribution pattern of total dissolved nitrogen (DN) in September 2000 (Fig. 3C) and March 2001 (Fig. 3G) was very similar to the distribution of NH$_4^+$ especially when considering the discrepancy between the south-east and north-east part of the lagoon in September 2000 and the strong global impoverishment in March 2001.

Si(OH)$_4$ concentrations in the middle lagoon were mostly between 1 and 2 μM in September 2000 (Fig. 3A) and increased to values ranging between 3 and 5 in March 2001. Significant coastal increase in Si(OH)$_4$ concentrations to values of more than 6 μM were exclusively measured in Dumbea and Boulari Bays, the two partially sheltered bays subject to significant river inputs. Rivers are major providers of silica to the lagoon as Si(OH)$_4$ concentrations of more than 400 μM were measured in the freshwaters of the three main rivers. The March 2001 cruise occurred during the rainy season and after significant rainfalls and the joint decrease in salinity and increase of Si(OH)$_4$ concentrations in lagoon waters is a clear consequence of river inputs.

### 3.2. Water typology and main influencing factors

The results from a principal component analysis (PCA) combined to a cluster analysis provided a synthetic classification of the water bodies in response to the respective importance of the main sources of influence. Results from the PCA (Table 2) showed axes 1 and 2 accounted for 78% and 74% of the total variability in September 2000 and March 2001, respectively, and hence could be unambiguously considered as the two main structuring factors.

![Fig. 4](image-url)Principal component analysis variables – representation of the variables as a function of axes 1 and 2 from the principal component analysis for September 2000 and March 2001 sampling cruises.

**Table 2**

<table>
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<tr>
<th>Component rank</th>
<th>1</th>
<th>2</th>
<th>3</th>
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<tr>
<td>Eigenvalue</td>
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<td>1.86</td>
<td>0.87</td>
<td>0.66</td>
<td>0.39</td>
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<tr>
<td>Proportion of variance (%)</td>
<td>62.92</td>
<td>15.5</td>
<td>7.29</td>
<td>5.52</td>
<td>3.21</td>
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<tr>
<td>Cumulative proportion (%)</td>
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<td>78.43</td>
<td>85.71</td>
<td>91.24</td>
<td>94.45</td>
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<tr>
<td>March 2001</td>
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<tr>
<td>Eigenvalue</td>
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<td>1.30</td>
<td>0.82</td>
<td>0.74</td>
<td>0.38</td>
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<td>76.35</td>
<td>83.21</td>
<td>89.39</td>
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PO$_4$\textsuperscript{3-} and PON ($r = 0.92$), turbidity ($r = 0.90$) and NH$_4^+$ ($r = 0.87$). Being essentially correlated with trophic status parameters, axis 1 could be considered as indicative of an enrichment gradient from oligotrophic on the negative side to eutrophic on the positive side. Axis 2 which accounted for 15.5% of the variability was correlated in decreasing order with: salinity ($r = 0.82$); DN ($r = -0.62$); silicates ($r = -0.57$) and NO$_3^-$ ($r = 0.54$). Axis 2 could be related to an oceanic versus river gradient from oceanic salted waters on the positive end to slightly desalted waters with increased river borne silica, DN, and NO$_3^-$ on the negative end. It must be mentioned here that inverse salinity gradients might occasionally develop inshore when strong draught conditions associated to ENSO events occur.

In March 2001 (Fig. 4b), axis 1 which accounted for 63.9% of the variability alone was positively ($0.84 < r < 0.95$) correlated with: PO$_4$\textsuperscript{3-}, PON, POP, DP, chlorophyll \textit{a}, pheopigments and turbidity, again indicating an enrichment gradient from oligotrophic on the negative end to eutrophic on the positive end. Axis 2 which accounted for 10.2% of the variability was correlated with NO$_3^-$ ($r = -0.71$), silicates ($r = -0.51$) and salinity ($r = 0.44$), indicating a gradient from oceanic salted waters on the positive end to slightly desalted waters and increased river borne Si and N on the negative end. The PCA distribution of environmental variables was strongly convergent for both sampling occurrence and also converged with results from a recent PCA analysis conducted on environmental variables in the Great Barrier Reef region (Fabricius et al., 2005) that identified two major influencing factors strongly comparable to those identified in the New Caledonia lagoon.

The combined PCA/cluster analysis for September 2000 (Fig. 5a) allowed for the distinction of six classes. Class 1, 2 and 4, respectively accounting for 41, 25 and 6 stations over a total of 87 stations (88%) sampled during the cruise, were disposed along a
diagonal axis (grossly from stations A03 to D48). The sampling stations gathered in class 1 were essentially located in the south-western offshore part of the lagoon and close to reef passages, indicating a major oceanic influence. Stations from class 4 were exclusively located in the inshore part of the bay of Dumbéa and their PCA projection is a consequence of: (i) a negative correlation with axis 2 corresponding to fresh water inputs from the Dumbéa River, (ii) a positive correlation with axis 1 corresponding to a moderate enrichment in trophic status. Stations from class 2 which were distributed in-between were located in the north-eastern part of the lagoon, in the open bay of Boulari and in the entrance of other bays, indicating intermediate conditions. This diagonal ordination therefore can be clearly attributed to a natural continuum between oceanic and inshore (freshwater + terrigeneous nutrients) sources of influence corresponding to an inland aging of the water bodies as shown by the water residence time indexes used as explanatory variables (Fig. 4a) (see also Oullion et al. (2010)). Therefore, even though the biogeochemical composition of 88% of the water samples collected in the lagoon was exclusively commanded by this oceanic to inshore continuum, which therefore appeared as a driving constrains acting at the scale of the whole lagoon, it only explained for a modest fraction of the overall spatial variability. Class 3, 5 and 6 respectively gathered 8, 5 and 2 sampling stations that strongly departed from the previously identified oceanic to inshore continuum. Such a distribution mainly resulted from a strong positive correlation with axis 1 corresponding to enrichment in trophic status. The distribution of Sainte-Marie Bay stations (prefix N) along the trophic gradient was consistent with their location along the entrance (N28) to the inner part (N04 and N05) of the bay transect. Stations N04 and N05 located in the most inshore part of Sainte-Marie Bay could be considered as strongly influenced by anthropogenic eutrophication due to inputs from poorly to untreated waste water discharges. Finally, four among the five stations that formed class 5 were located in Dumbéa Bay close to the city of Nouméa and the Dumbéa river estuary therefore experiencing combined terrigeneous and anthropogenic inputs.

The combined PCA/cluster analysis for March 2001 (Fig. 5b) showed a slightly higher dispersion of the data set along axis 1 and yielded a six classes typology very comparable to September 2000 typology. Class 1, 2 and 4 with 45, 11 and 4 stations, respectively, over a total of 86 stations (70%) were organised along a diagonal offshore versus inshore continuum similar to the one identified in September 2000. Class 3, 5 and 6 respectively gathered 18, 3 and 1 stations, respectively, strongly departed from the offshore versus inshore continuum due to a significant influence of the eutrophication factor, with stations from the inshore parts of Sainte-Marie Bay (N04 and N05) and Koutio Bay (D64 and D65) again appearing as the most strongly impacted.

The typology strongly converged for the two sampling occasions even though they corresponded to very different seasons with significant changes in the absolute value of each parameter. The most important feature in that typology relates to the fact that a very limited number of artificially eutrophized stations (12–30%) accounted for most (~80%) of the spatial variability. Scientists working in meso-eutrophic temperate marine environments might consider the observed absolute level of trophic enrichment as insignificant but our results demonstrate that even when delivered in moderate amount nutrient anthropogenic inputs generate a very significant departure from natural equilibrium hence playing a determinant role in structuring environmental conditions and associated biota responses. Such a major specificity of eutrophication processes in coral reef oligotrophic ecosystems still has to be fully perceived by the scientific community as well as by environmentally concerned decision makers. Additionally, the typology permitted to identify key variables that were most closely linked to the two major influencing factors and could be specifically studied in term of temporal variability. With a variable versus factor correlation of more than 0.9 in both occasions against axis 1, chlorophyll a unambiguously stood as a good indicator of trophic status. With a variable versus factor correlation of 0.7 in September 2000 and 0.44 in March 2001 against axis 2, salinity stood as one of the best indicator of oceanic versus freshwater influences, siliicates also appearing as a potentially valuable indicator of such an influence. Beside those two essential indicators, variability of some other parameters commonly used in environmental studies (turbidity, inorganic nutrients, and particulate organic matter) was also investigated.

3.3. Vertical structure

High resolution information on the vertical distribution of key parameters (temperature, salinity, turbidity, and in situ chlorophyll related fluorescence) in the water column is a prerequisite to assess the representativity of discrete water sampling. Comparison of profile measured at different time required the conversion of data to relative data expressed as

\[ X_{rd} = \frac{|X_m| d}{X_{prof}} \]  

where \( X_{rd} \) was the calculated relative concentration at depth \( d \), \( |X_m| \) was the measured concentration at depth \( d \) and \( X_{prof} \) was the average concentration over the whole vertical profile, vertical heterogeneity being evidenced by the divergence from a ratio value of 1. Profiles recorded at a single sampling station during the whole survey were plotted together as a function of depth (Fig. 6). Only three data sets were plotted corresponding to stations that were identified previously as representative of oceanic influence (stations A03), intermediate lagoon (station D41), and eutrophic areas (N04) groups.

Temperature and salinity displayed a very moderate heterogeneity with insignificant stratification. Turbidity distribution showed frequent occurrence of a significant bottom nepheloid layer reaching values of 4–6 times the profile averaged turbidity value and generally limited to a few meters above the benthic boundary layer. In the inner and outer lagoon stations, a log-linear regression provided the best fit with \( R^2 \) values of 0.24 and 0.45, respectively. For chloropigments, despite occasional surface maxima, the most common trend observed in the outer and intermediate lagoon corresponded to an increase with depth in chlorophyll concentrations. Curve fit from log-linear and linear regressions yielded very similar results. This vertical trend was not observed at inshore stations certainly because shallow water conditions did not allow for a significant vertical gradient. Considering the weak density stratification and the prevailing euphotic conditions (nonpresented irradiance profiles), the increase in chlorophyll concentration with depth could be explained by photo-inhibition in the upper layers and/or nutrient inputs from the benthic system. Very little is known about photo-inhibition but that process would not be of significance beyond a few meter depths. Furthermore, the second hypothesis is strongly supported by recent work on benthic metabolism and biogeochemical modelling in the New Caledonia lagoon that concluded that pelagic primary production was strongly controlled by benthic recycling and nutrient release in the water column (Bujan et al., 2000; Grenz et al., 2003; Pinazo et al., 2004).

3.4. Temporal variability

The study of short term temporal variability combining vertical profiling and discrete water sampling was first conducted on selected typical sampling stations with a 30 min frequency over peri-
Little variability was observed in the middle lagoon (stations M33 and A24), demonstrating day/night trends to be insignificant. However, the occasional passage of 3–5 m thick sub-surface lenses of slightly desalted and chloropigment enriched
water were observed on eight occurrences over 25 h at the most offshore station (A24). Previous results from hydrodynamic modeling strongly suggest that surface desalted water lenses could originate from the southern part of New Caledonia mainland (Douillet, 1998; Douillet et al., 2001), their conservation as identifiable hydrologic subsystem being only possible under conditions of moderate wind stress and wave energy. The represented situation however can be considered as infrequent as the outer lagoon is generally subject to sustained trade winds resulting in strong hydrodynamic conditions, rapid renewal of water and water column homogeneity (Bujan et al., 2000; Douillet et al., 2001; Pinazo et al., 2004). Inshore, stations D47 in front of the Dumbea river estuary and N04 in the inner part of eutrophized Sainte-Marie Bay exhibited a much stronger temporal variability. In Dumbea Bay, the influence of Dumbea River (0.5 m$^3$ s$^{-1}$ on average) generated some moderate variations in salinity with no evident link to a day/night cycle while chloropigments clearly increased from morning to twilight and decreased from twilight to morning. In

Fig. 7. Analysis of high frequency temporal variability – interpolated plot of chloropigment (in situ fluorometry derived) and salinity profiles (30 min frequency) over 25 h time periods in four typical sampling stations (beware of different color/value scales). Black bars represent obscurity periods (irradiance < 1 μE m$^{-2}$ s$^{-1}$). Station A24 = outer lagoon (September 2000), station M33 = middle lagoon (June 2003), station D47 = inner bay (October 1998), and station N04 = eutrophic bay (October 1998).
concentrations were around 0.35 and decreased within a 1–3 NTU range afterward. Chloropigment during the 2 first days corresponding to the low salinity pulses pressure data). Turbidity irregularly increased from 1 to 9 NTU

maximum salinity values being reached at low tide (nonpresented

The 12 h period clearly related to the influence of spring tide, min-
cant decreases in salinity with a 12 h period during the 2 first days

followed by a long period with lower and more erratic variations.
The 12 h period clearly related to the influence of spring tide, min-
cant decreases in salinity with a 12 h period during the 2 first days

At station D47, in front of the Dumbea River, we observed signifi-
cant short term eulerian variability. At station D47, in front of the Dumbea River, we observed signifi-
cant short term eulerian variability.

Slow water renewal and significant terrestrial and anthropogenic

inputs generated strong gradients on short distances and even a

limited displacement of water masses proved to generate signifi-
cant short term eulerian variability.

The analysis of monthly variability of environmental variables

was conducted over the 1997–1999 period on a total of 32 sam-
pling stations (Table 1) temporal variability trends between sta-
tions with very different average concentration levels were compared by considering relative concentrations according to:

\[ |X|_{r_1} = \frac{|X|m_t}{|X|_{surv}} \]  

where \(|X|_{r_1}\) was the calculated relative concentration at sampling time \(t\), \(|X|m_t\) was the measured concentration at sampling time \(t\) and \(|X|_{surv}\) was the average concentration over the whole profile, temporal variability being evidenced by the divergence from a ratio value of 1. Results from the sampling stations classified as middle lagoon from the PCA typology (class 1, \(n = 14\)) were plotted and compared to data from stations influenced by terrigeneous (D47) and anthropogenic (D01 and N04) inputs (Fig. 9). Only chlorophyll \(a\), ammonia and nitrates were retained as they were identified by the PCA as the most structuring non conservative variables. In the middle lagoon, chlorophyll \(a\) showed a relatively unambiguous seasonal variability with a maximum value at the end of May, hence just before reaching minimum water temperature (southern hemisphere), corresponding to minimum values in \(\text{NH}_4^+\) (recycled N) and maximum values in \(\text{NO}_3^-\) (new N). Such a seasonal trend in chlorophyll \(a\) concentrations has already been reported for the New Caledonia lagoon (Binet and Le Borgne, 1996; Le Borgne et al., 2010) as well as in the oceanic province around New Caledonia (Dandonneau and Gohin, 1984) the later author attributing the phytoplankton bloom to the rise of the nutricline due to winter cooling of surface

Fig. 8. Analysis of high frequency temporal variability – mooring records (10 min frequency) of salinity, turbidity and in situ fluorescence at 3 m depth in a bay influenced by river inputs (Dumbea Bay, station D46) and in a bay subject to eutrophication (Sainte-Marie Bay, station N20) in June 2001.
waters. Even though that hypothesis might appear to be supported by the observed concurrent increase in chlorophyll a and NO$_3^-$ (Fig. 9b and c), the occurrence of a similar cycle in NO$_3^-$ concentrations in estuarine systems with ambient concentrations several folds higher than in the middle lagoon cast some doubts on its alleged oceanic origin. The detailed analysis of such a process was not within the scope of this article but the study of the forces driving such an unusual seasonal trend should require some future attention as it might relate to the coincident occurrence of episodes of calm weather allowing for the build up of phytoplankton biomass. That seasonal trend was also observed for stations D47 and D01 but with some significantly higher variability especially at D01. Variability at station N04 was important and did not match the seasonal trend observed for other stations. In that later case, the relatively constant daily supply of anthropogenic nutrient apparently results in a non season-dependent variability. Chlorophyll a concentrations during the 1998–1999 warm seasons were significantly higher than during the 1997–1998 warm seasons. Such a difference could be related to the occurrence of a severe El Niño episode in 1997 resulting in a very dry period in the south-western part of the Pacific Ocean, the return to normal conditions resulting in strong rainy episodes in January 1999. The 1997 ENSO event proved to have a detectable impact on temperature and salinity variations in the New Caledonia lagoon (Ouillon et al., 2005). The general trophic level of the lagoon is naturally low due to its rapid flushing by oligotrophic oceanic waters (Jouon et al., 2006) but is however sustained by terrigeneous inputs. In such an environmental context, the occurrence of El Niño events provoking severe periods of droughts in the western part of the Pacific Ocean might significantly lower the inputs of terrigeneous nutrients hence decreasing phytoplankton nutrient sources. Beyond the direct effect on plankton population, such a decrease would result in the food limitation of lagoon suspension feeders. Such a stressing factor would combine with other stresses that have been listed as potential triggering factors to coral bleaching and the various epidemic crises recorded in coral reef environments during ENSO events (Lafferty et al., 2004).

Using the variation coefficient (100 $\times$ standard deviation/average) to compare hourly versus monthly variability (Table 3) showed that the daily variability was generally close to monthly variability for dissolved material and significantly lower than monthly variability for particulate material, a result that mostly converges with the reported pattern of phytoplankton in the New Caledonia lagoon (Torreton et al., 2010). Those results demonstrate that the variability at various time-scales of biogeochemical parameters is a constraining factor that must be properly assessed when designing environmental monitoring projects.

### 4. Conclusions

Under pristine conditions, waters in the lagoon of New Caledonia would be organised along a continuum gradient between two sources: (i) water with an oceanic signature and (ii) coastal water identified by slightly lower salinities and higher Si(OH)$_4$ concentrations together with a modest enrichment in nutrients and particulate organic material. The Dumbea Bay combining long water residence time together with significant river inputs clearly stand at the extreme end of the terrigeneous influence gradient. Results showed that such a natural continuum would generate low variability in water chemistry and trophic status, most of the outer lagoon stations experiencing very similar environmental conditions. That absence of a strong environmental constraining gradient in the outer lagoon could be considered as a factor favouring the expression of a strong biodiversity as spatially heterogeneous factors mostly related to habitat complexity could express themselves as the main environmental constraints hence yielding strong biota spatial variability.

Apart from this naturally occurring gradient, the parameters measured allowed for the unambiguous identification of an
anthropogenically driven eutrophication gradient mostly related to untreated sewage release. Eutrophication hotspots were constrained to urbanised embayments such as Koutio Bay, Grande Rade and Sainte-Marie Bay, where the most specific signatures were measured. The multivariate analysis of the dataset clearly allowed discriminating between natural eutrophication of aged water bodies and additional eutrophication due to anthropogenic inputs. Using such data treatment approaches is essential to accurately interpreting biota response to alleged environmental stress, a step which has already been applied to the New Caledonia lagoon (Dumas et al., 2007; Sasal et al., 2007). It is also important to stress that eutrophication does not relate to bulk concentrations but is a dynamic process leading toward the increase from an initial trophic status. In this regard, eutrophication of oligotrophic coral reef lagoons must be fully acknowledged as a very specific process in which even slight increases in trophic status may result in very significant shifts in the structure and composition of pelagic primary producers (Jacquet et al., 2006) consecutively impacting the whole biogeochemical cycle.

Except for canyons where a sharp stratification in two distinct layers might occasionally occur due to open ocean water intrusion, water bodies from the open lagoon were generally feebly stratified with moderate to no temperature and salinity gradients. Chlorophyll a concentrations did not always obey such a vertical stability rule as concentrations often significantly increased with depth, certainly as a consequence of nutrient release at the water–sediment interface. That clearly indicated a strong relationship between pelagic production and benthic recycling. Salinity and temperature gradients were more pronounced inshore, in bays where calmer hydrodynamic and wave regimes prevailed, but due to their shallowness no clear chlorophyll a vertical gradient could be observed.

Short term (~hourly) variability was low in the outer part of the coral reef lagoon but strongly increased inshore mainly due to the displacement of water bodies with contrasted biogeochemical signatures. Hourly variability was generally close to monthly variability for dissolved material and lower than monthly variability for particulate material. Despite such variability, we observed that severe dry weather conditions due to the 1997 El Niño significantly depleted the lagoon trophic status. Therefore, ENSO might be responsible for food limitation of lagoon suspension feeders, a factor that could play an additional role in coral bleaching and the various epidemic crises recorded in coral reef environments during ENSO events.

Finally, the general strong significance of short term variability has rarely been documented and represents a factor that need to be seriously assessed before any conclusion on environmental degradation could be drawn. On an environmental management point of view, such variability represents a strong limitation to the definition of reliable biogeochemical indicators of environmental status and the implementation of environmental monitoring programs in coral reef lagoons would require three major steps: (i) selecting biogeochemical parameters adapted to environmental stress, (ii) establishing a proper definition of local guidelines for each selected biogeochemical parameter, (iii) defining alert/control strategies adapted to evidenced temporal variability.

Acknowledgements

This work was financially supported by the French Institut de Recherche pour le Développement (IRD) and by the French Programme National Environnement Côtier (PNEC). We express special thanks to the staff of IRD Research Vessels Alis, Coris and Aldric and to the technical staff of the IRD Centre in Nouméa.

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